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APPLICATION OF  
FLEXIBLE AUTOMATION  
TO SHIP CONSTRUCTION

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ABSTRACT

Computer-aided design and flexible automated manufacturing technologies presently available and currently under active development can provide the keys to improved productivity in shipbuilding. The specific applications of these technologies, implemented or proposed for other more structured and product-form stationary industries, are not generally applicable to shipbuilding. The problem addressed by this project is the research and analysis of the potential mating of advanced productivity improvement technologies to shipbuilding. Formal criteria are proposed for the selection of ship construction operations and the establishment of their priority as candidates for further study of automation potential.

## INTRODUCTION

The concept of applying flexible automation for productivity improvement is widely accepted throughout many metals-working industries. Applications of these technologies are, however, just beginning to emerge in ship construction. This is largely due to the differences in the workpieces and workplace existing between ship construction and other metals-working industries. Lists abound of ship construction processes suggested as candidates for automation. Relevant criteria are needed to make rational choices in ordering the candidates. It is not surprising that the criteria developed for other metals-working industries are not strictly applicable to ship construction.

Selection criteria commonly proposed in robotics literature are examined with respect to the particular characteristics of ship construction. On the basis of this discussion, certain of these criteria are rejected as inappropriate or insensitive in the ship construction environment. Additional criteria with particular applicability to ship construction are proposed. Automation opportunities are plentiful and shipbuilder's resources are limited. The question is how to decide the best places to invest time and capital.

We can, however, develop an applicable set of criteria by examining the constraints and realities of the ship construction industry.

## ECONOMIC FACTORS FAVORING FLEXIBLE AUTOMATION

Present and foreseeable future world realities facing the United States make it imperative that shipbuilders supply to the Navy evermore capable ships at evermore improved acquisition costs. Much of the acquisition cost of a ship is beyond the direct control of the shipbuilder. The cost of material, machinery, equipment, and weapon systems is largely determined by the suppliers. The unit cost of labor to complete the contract

design, acquire the material, and construct the ship is related to the prevailing wage for similar work. What the shipbuilder can control is the effectiveness with which material is used and labor is expended in realizing the completed ship.

Traditional organization of ship planning, design, construction, and testing is established along the boundaries of structural and functional systems that comprise the ship. The form of organization evolved in parallel with the evolution from simple hulls to modern surface combatant ships. Masts were stepped into simple hulls. Bulkheads and decks were incorporated to improve the ship structure. Cuddies and then deckhouses added accommodation for the ship company. These examples and many more have direct evolutionary counterparts in a modern ship; each separately conceived and established. The strength of this form of organization is the visibility of individual systems and the ease of monitoring the progress of these systems toward completion. The traditional organization, however, forces the shipbuilder strictly to adopt job shop methods and to accept the inefficiencies that attend that way of doing-work.

Many shipbuilding methods are the evolutionary result of something that was tried in the past and adopted simply because it worked. The issue is complicated by the very large size and mass of a ship and by the multitude of machinery, equipment, and functions that must be incorporated in the ship. During a ship construction cycle, the requirements of a ship can change and technical development may offer the opportunity for improved ship capabilities. Only a small amount of the work is exactly repeated, even between ships for the same class. Thus, shipbuilding is a highly unstructured and very labor intense industry.

Foreign shipbuilders have provided ample evidence that significant' productivity gains can be achieved for certain classes by a form of organization that disaggregates the ship along construction boundaries. This procedure is repeated to achieve ever simpler parts with ever reduced geometric, material, and manufacturing processes individually. In accomplishing this procedure, great volumes of information are created and exchanged among

the ship owner and the shipbuilder's operating organizations. Finally, families of similar parts are fabricated using repeatable manufacturing processes and suitable fixtures to achieve the accuracy required for assembly into the ship. The gains of this procedure are realized by taking advantage of the production economies of scale.

During the previous two decades, many of the manufacturing concepts perfected in foreign yards have been adopted in modified form to suit local conditions by shipbuilders in the United States. Disaggregation of a complex surface combatant ship to a level supporting parts fabrication on fixed tooling remains, however, a very large and difficult task. Because of the complexity of these ships, clearly any manufacturing procedure used to fabricate the required components will necessarily be data-driven.

Computer-Aided Design and flexible automated manufacturing technologies presently available and currently under active development can provide the tools for improved productivity in shipbuilding. The specific applications of these technologies, implemented or proposed for other more structured and product-form stationary industries are, however, not generally applicable to shipbuilding.

## SHIP CONSTRUCTION FACTORS DISCOURAGING FLEXIBLE AUTOMATION

Having described the economic factors favoring the introduction of flexible automation in ship construction, it is also necessary to describe the factors discouraging the introduction of these technologies. The list of discouraging factors given here is not new. All of the factors in this list have appeared in one form or another in previous papers [1]. Each of these discouraging factors must be addressed by any successful application of flexible automation to ship construction.

Ships are generally built on a one-off basis or in small classes of a given type. Larger classes are usually comprised of several subclasses, each subclass differing significantly from the others. Production runs of standard ships are rare. Even within a specific ship,

the utilization of duplicate parts is very low. Foundations, piping assemblies, and structural assemblies tend to be individually designed to accommodate local details within the ship.

In addition to the use of few parts that are duplicated many times throughout a ship, ship designs tend to be geometrically very complex and to provide confined access to much of the work. Much of this could be relieved, at least conceptually, through redesign of the ship. This would require a radical reappraisal of design criteria and objectives. This would also likely require resolution of numerous conflicts with Navy specifications and the design rules of the classification societies.

Ship parts and assemblies tend to be large when compared with industrial robots. Ship parts and assemblies tend to be approximately planar, or boxlike. These shapes mate poorly with the spheroidal working envelopes of many industrial robots. The dimensional tolerances of ship parts and the low precision with which they are placed onto each other are difficult to accommodate with existing robot controllers. What is needed are flexible automation systems specifically developed and suited for ship construction. This development will be costly and require significant time to accomplish. For this reason, custom ship construction flexible automation systems may be difficult to economically justify.

In isolation, many ship construction operations are technically feasible. For flexible automation, parts presentation tooling and extra handling may be required, both upstream and downstream of the automation station. These costs may exceed the benefit achieved. The investment in isolated automation can preclude the economic viability of developing a broader ' system encompassing adjacent operations.

There are very finite bounds to the flexibility which can be obtained with any production automation system. These systems will always be limited to functioning in the specific class of production situations for which they are designed. A craftsman possesses far greater adaptability and is provided with many more degrees of mechanical freedom than any



mechanical production system. The strength, speed, endurance and exactness of a craftsman are limited. The nature of ship construction operations necessitates a continuing concert working relationship between craftsmen and flexible automation systems. Craftsmen cooperatively functioning in concert with flexible automation systems cannot be subjected by the system to unacceptable levels of hazard.

Viewed in total, the factors discouraging flexible automation in ship construction are the expression of four very real concerns:

Reduction of the economic benefit of the flexible automation system due to the programming costs associated with large numbers of differently configured parts and confined access.

Economic justification of the greater investment required to develop flexible automation truly suitable to ship construction.

Reduction of the economic benefit of the flexible automation system due to additional facility and special practices, particularly part presentation tooling and part, required as a consequence of mechanization.

Availability of adequate personnel safety measures which are technically and economically feasible.

#### BASIS FOR ESTABLISHING EVALUATION CRITERIA

Certain flexible automation systems proposed for ship construction will be feasible in the sense that the required development can be accomplished with technology available currently or anticipated in the immediate future. Some can be made adequately safe in the sense that technically and economically feasible measures to limit the hazard to craftsmen functioning in concert with the system are available. Some will be useful in the sense that system operation accomplishes manufacture of ship subproduct or class of subproducts without undue disruption upstream or downstream. Some will be potentially profitable in

the sense that the productivity improvements and other benefits anticipated as a result of system operation return the necessary investment in a manner attractive to the owners.

Clearly, successful flexible automation systems must belong to the subset of feasible proposals which are co-jointly adequately safe, useful, and potentially profitable.

Given the limited availability of resources, criteria are needed to rationally establish priorities for development. Many such criteria, appropriate for factory situations, have been proposed in the literature of flexible automation. The constraints of ship construction force modification of these criteria. The resulting modified criteria are **no** longer quite as simple or straightforward to apply, but realistically account for factors unique to ship-building.

The modified criteria may be used in a qualitative analysis or 'an approximate qualitative analysis as a linear combination of weighted factors. Since some of the modified criteria **embody** complex concepts, a level of uncertainty may exist in measuring proposed flexible automation systems under these criteria. Utility theory includes the computational tools for an exact analysis in the presence of uncertainty. An explanation of these computational tools is beyond the scope of this discussion.

## ERGONOMICS

Reduction of negative ergonomic factors associated with current production methods are prominent among factory automation project evaluation criteria. These include reduction of hazard to personnel, strenuousness and tedium. These factors lead to unacceptable accident rates, absenteeism, employee turnover, and rework. Such things are proper concerns of shipbuilders; however, use of these criteria tacitly presumes wide variation in negative ergonomic factors with relatively uniform difficulty and technical feasibility of automation. With ship construction operations strenuousness is relatively uniform. Job details **change** daily and tedium in the factory sense does not exist. Hazardous ship construction jobs

such as working inside tanks and voids are most often associated with the most highly unstructured work environment and are therefore the least technically feasible for automation. These criteria are not sensitive indicators of the merits of ship construction automation projects.

## FEASIBILITY

Contrary to popular belief, the feasibility of flexible automation projects is not just a binary proposition of feasible and infeasible. Between the extremes of impossible and assured, there are innumerable shades of grey, ranging from difficult to easy. Different configurations to resolve the technical objective may have very different feasibility.

Establishing technical feasibility of factory flexible automation projects involves identifying manipulation machines which have a sufficiently large working envelope, are capable of the necessary motions and precision, and are rated for the necessary payload. Factory flexible automation projects are often a direct replacement for manual operations and the process tools used are a direct extension of the process tools used in the manual operation. Parts handling equipment and even the necessary sensor systems are generally available as commercial items. The areas of primary technical risk are achieving critical part alignments and avoiding manipulator collisions.

## DEXTERITY

Ship construction adds the dimension of scale, adaptivity, and rapid product variation to consideration of technical feasibility. The dexterity and precision of tool motion required with respect to a large scale ship construction is the same as required for much smaller workpieces. The working envelope necessary is far beyond the capabilities of commercial robots. A very large special design robot is required to manipulate the tool over the workpiece, or else a secondary means of positioning a smaller robot over a local worksite is required. Manipulation machinery of this size can vibrate the tool through greater distances

than the process tolerances. Additionally, the fundamental and low order harmonic frequencies of the large links impose new constraints on the selection of system control frequencies.

## WORK RATE

The rate at which **any** production system can accomplish work is the product of the tool work rate, the number of tools which can be operated simultaneously on the workpiece, **and** the proportion of time the tools are accomplishing work. Schedule constraints usually require multiple craftsmen working in concert to achieve timely completion of ship subassemblies. Ship construction flexible automation systems are bound by the same schedule constraints. That means that these systems must achieve higher tool work rates, apply multiple tools to the workpiece, and increase the proportion of time that the tools are engaged with the workpiece. Each of these options affects the system technical feasibility.

## FLEXIBILITY

Modern practice organizes the great variety of ship construction workpieces into process lanes. The work is partitioned such that the production problems encountered become generic to a given process lane and the total work content is relatively uniform between units in the lane. Process lanes, by definition, exhibit **many** of the properties of factory assembly operations subject to rapid product variation. These properties become evident in considering panel construction, generation of parts from structural shapes and the assembly of marine closures. In each case, time and labor required to handle and position parts or stock, to index the automated production system to the workpiece, and to generate and load the program become very important relative to the total costs to product the workpiece. Automatic program generation from the engineering database is almost mandatory. Scott and Husband [2] have developed a principle of fixity relating the

costs of fixed and flexible portions of an automated assembly system to the time permitted to set up the system for a particular product and the total system for a particular product and the total system time allocated to **that** product. The proportionality constant has not been calibrated for ship construction automation projects. The shape of the curve is instructive as an indicator of proper balance in the design of a ship construction automated system. The indication heavily favors investment in flexibility.

## LOW AGGREGATE COMPLEXITY

Low aggregate complexity will not independently establish the feasibility of a flexible automation system. Overly complex\*systems are more difficult to integrate and to maintain than less complex systems. The higher the system complexity, the more likely that the performance of **one** or more features will constrain overall system performance to **some-**thing less than the design goals. Low aggregate system complexity is an indicator of the probable success of otherwise technically feasible systems. This criterion tends to form truly simple systems. It also favors systems which directly resolve more complex production problems.

Lights, bells, and whistles impress, but like the grade school adage, “Pretty is as pretty does”. Operators need direct access to minimal sets of functional commands specifically related to causing accomplishment of the task to be done. This will permit the operator and other personnel working in concert with the system to function as craftsmen. Adequate provision for the safety of these people is paramount.

## DIVISION OF LABOR

Machines are capable of greater speed and consistence, and better able to withstand process related stresses (force and vibration, noise, heat, smoke and fumes) than are personnel. Craftsmen are better able to deal with unstructured work situations, and can apply many more degrees of mechanical freedom. Far greater dexterity of ship construction

operations dictates manual operators exercise at least supervisory control of flexible automation systems. Ergonomic concerns are well served by evaluating how effectively proposed ship construction flexible automation projects achieve safe and suitable division of labor between man and machine.

## UTILITY

Flexible automation systems working in factory environments are often able to operate with a fair degree of autonomy and isolation from the rest of the plant. Parts are presented to the system in a fixed location and orientation. The system accomplishes its function and the part is returned to a fixed location. This is all very fine and well, but in ship construction, efficient accomplishment of a work function is not enough. What is necessary is system utility. Utility means that the system accomplishes a complete task, preferably completing a ship subproduct. This function must be accomplished in such a way as to complement and not add work to adjacent operations. The system must be capable of adapting to the handling practices, parts locating capabilities, and dimensional tolerances of upstream manual ship construction practices. When the system has completed its work, the subproduct made should be ready for the next stage of assembly, dimensionally compatible with other portions of the ship and not requiring adjustment or dimensional survey. The productivity of the system must be capable of achieving balance with adjacent operations. 'This criterion favors systems which function to combine or subsume multiple operations as a consequence of mechanization. Systems which accomplish larger work contents are favored as are those systems which require the least accommodation in adjacent operations.

## PROFITABILITY

As in all things related to business, ship construction flexible automation projects must be evaluated on the basis of potential profitability. This follows from the first axiom of business which establishes that the purpose of a business is to maximize the wealth of the

owners [3]. The operative word is “wealth”, and not cash. Wealth has at least two components, cash or value in hand, and the power ‘to generate even more wealth. It is unwise to neglect either component. Excessive capital investment risks a market shift and a potential shortage of operating funds.

American business is learning again that programs to maximize only cash are hoarding [4]. It is something like a farmer storing his entire crop for many years in anticipation of higher prices. He has no seed for a new crop. Productive farmers pass him by. Sooner or later, the stored crop will not germinate. We need a balance of cash management for today and investment in order to be in the ship construction business tomorrow.

This leads to the second axiom of business, which identifies that because of tomorrow’s risk, value in hand has more worth than the same value tomorrow. Be prepared to show potential profitability of proposed flexible automation projects on the basis of discounted value. Make sure your accountant not only considers cash flow, but also the value of improved competitive position provided by flexible automation systems.

For a flexible automation system, profitability means accomplishing a ship construction task at a significantly lower cost than the actual cost present methods and the cost of capitalizing the system. Profitability will favor feasible systems and accomplish a high work content. It will also favor replacement operations which have under present methods a large necessary no value added work content which can be subsumed as a consequence of mechanization. This includes such things as reassuring marking, layup, positioning and orientation. It also includes lofting, template making and maintenance, and detail work planning. The profitability criterion will favor projects with high utilization factors.

## CONCLUSION

Ship construction is a unique industry. Traditional criteria for evaluating flexible automation projects are not always appropriate. New criteria are needed. These criteria

are, however, complex and comprised of several components. Flexible automation projects exhibiting high levels of feasibility, safety, utility, and potential profitability will be successful when they are implemented in ship construction.

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